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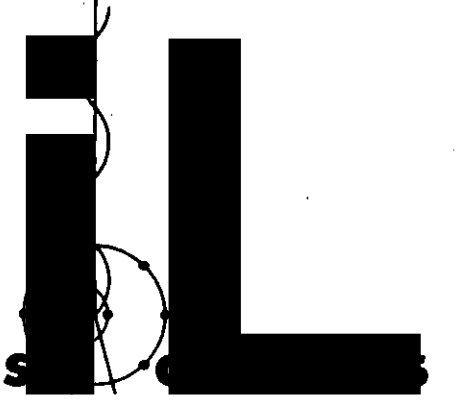

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HAZARD CLASSIFICATION TEST OF GAU-8 AMMUNITION BY BONFIRE COOKOFF WITH LIMITED AIR SAMPLING

by

J. C. Elder, M. I. Tillery, and H. J. Ettinger

ABSTRACT

A standard hazard classification test of GAU-8 ammunition was performed August 26, 1975, for the U. S. Air Force Armament Laboratory (AFATL). Fragment pattern scoring following bonfire cookoff of 180 live rounds indicated only one shell base fragment was thrown beyond 400 feet by shell case disruption. Uranium aerosol dispersed by burning of depleted uranium penetrators within the ammunition was detected at five air samplers placed near the bonfire.

I. INTRODUCTION

The U. S. Air Force Armament Laboratory, Eglin Air Force Base (AFB), Florida, requested assistance in performance of a storage and handling hazard classification test (bonfire cookoff) for a new type of 30-mm ammunition. The armor piercing version of this ammunition (GAU-8) contains a core of depleted uranium (DU), which is classified as a radioactive source material and a toxic heavy metal. This work was performed under an interagency agreement between Energy Research and Development Administration (ERDA) and the U. S. Air Force (USAF).[1] The usual objective of a bonfire cookoff test, fragment pattern scoring, was supplemented by limited air sampling for indication of airborne DU. The air sampling aspect became more important after a preliminary bonfire test of a single penetrator indicated major loss of mass from the penetrator and significant airborne DU collected nearby. The full-scale bonfire cookoff of 180 live GAU-8 rounds was conducted to (1) fulfill the fragment mapping requirement and (2) confirm the presence of airborne DU released during this standard test. Measurement of aerosol size characteristics and mass concentrations was not considered a realizable objective under the field test conditions and funding constraints.

II. BONFIRE TEST OF ONE GAU-8 PENETRATOR

Lack of information regarding the effect of a bonfire on DU prompted a small scale test with a limited amount of DU and no propellant. A single GAU-8 projectile was exposed to bonfire conditions and examined for loss of material. The DU penetrator was enclosed in an aluminum mockup of the production projectile and laid on a 2 x 12 pine board supported by two sand-filled paint cans 30-cm high. Four chromel-alumel thermocouples were arranged in a semicircle 0.32 cm above the surface of the mockup. Pine boards (1 x 4 or smaller) were piled under and around the mockup to a thickness of at least 46 cm (18 in.) and ignited by 19 liters of diesel fuel. The

mockup projectile remained in the bonfire about 28 min. Temperatures remained fairly low (600°C) for 15 min until coals settled around the mockup, then moved above 900°C. Peak temperature was 1040°C; average temperature over the last 5 min of the test was about 975°C. A stiff breeze was blowing throughout the test.

The penetrator was allowed to cool and mechanically cleaned by roughing lightly with the teeth of pliers. Cleaning consisted of removal of loose or soft material down to base metal identified by appearance of pyrophoric sparking when scuffed. The penetrator broke easily into two fragments: a larger piece of DU and a smaller piece consisting of fused aluminum around a soft, porous core of DU. About 18 g of debris (wood ash, Al, U oxide) was removed by the cleaning operation. The penetrator was altered significantly by exposure to the bonfire as can be seen in Fig. 1. Table I offers a comparison of several characteristics of the penetrator before and after the fire. The penetrator experienced a significant reduction in density and a loss of at least one-third of its mass. Complete ashing of the penetrator would probably have occurred if more fuel and time had been available. An air sample taken about 3 m away indicated 64-μg uranium collected on the 18 x 25-cm Whatman 41 filter, confirming the release of a uranium aerosol.

Fig. 1.
Test penetrator fragments after mechanical cleaning. Spare penetrator included for comparison.

III. BONFIRE COOKOFF OF LIVE AMMUNITION

A. Experimental Apparatus and Techniques

Overall test direction, site and test preparations, air sampling, sample analysis, test evaluation, reporting, and site restoration were the responsibility of the Industrial Hygiene Group (H-5). Communications, site safety, squib firing, live shell disposal, and onsite supervision was provided by the Pin Diagnostics and Neutron Measurements Group (M-4). Meteorological support was provided by the Environmental Studies Group (H-8); photographic documentation by Graphic Arts (ISD-7); and ammunition storage and handling by Weapons Engineering (WX-3). Procedural guides were contained in the H-5 General Test Plan and M-4 SOP 11 "Explosive Burning Experiments."

The largest cleared and reasonably level area available for this test was R-Site, firing points E-F. Its long history of tests involving explosives and uranium has left it relatively clear of large trees and completely unrestricted where a new source of uranium contamination was concerned. Its distance from the main technical area and Los Alamos townsite (~ 4.0 km) provided adequate safeguards relative to maximum uranium concentration if typical plume dispersion conditions for this time of year existed during the test.

The standard North Atlantic Treaty Organization (NATO) bonfire cookoff procedure calls for a 500-ft-radius circle to be cleared for detailed fragment scoring.[2] The R-Site clearing is about half that size, requiring a compromise agreement between Los Alamos Scientific Laboratory (LASL) and the USAF in which a 360° sector of 100-ft radius and a 180° sector of 400-ft radius received detailed scoring. The 100-ft-radius circle (360°) was scraped clean of all vegetation. Mowing and raking the semicircle to 400-ft radius provided an acceptable clearing for representative, if not total, pattern scoring. Scoring categories were specified to be shell (complete round), projectile (DU penetrator and Al jacket), shell base (thick section at bottom of the shell), and fragment (any thin section of shell separate from shell base).

TABLE I

PHYSICAL CHARACTERISTICS OF MOCKUP PENETRATOR

Characteristic	Original Penetrator	After Testing	
		Larger Fragment	Smaller Fragment
Mass (g)	298.16	144.49	61.29 (Al + DU)
Length (cm)	11.5	8.0	—
Maximum diameter (cm)	1.6	2.8	—
Minimum diameter (cm)	—	1.8	—
Wet displacement (ml)	16.0	22.4	13.0
Approximate density (g/ml)	18.5	6.4	4.7

The NATO procedure used by the U. S. Air Force for bonfire cookoff tests specified the general configuration of the stack and how it was to be ignited.[2] The general requirements were (1) five cases of 30-mm ammunition (180 rounds) stacked in a 2-on-3 array and banded together by an unspecified number of steel bands, (2) the ammunition placed on a platform 91 cm (36 in.) above ground level supported by two columns of sand-filled ammunition cases, (3) kindling no larger than a 2 x 4 packed around the platform and ammunition to a thickness of at least 46 cm (18 in.), (4) the stack soaked with 57 liters (15 gal.) of diesel fuel, and (5) ignition of the stack on two sides by electrically operated squibs. This procedure was followed with the minor exception that two 55-gal. drums were substituted for the ammunition cases to support the platform. One problem was encountered in maintaining configuration of the bonfire; the steel grating laid across the drums to support the ammunition cases sagged during the bonfire, allowing them to settle into the embers between the drums. How this affected the fragment pattern or DU fraction dispersed is not known since some penetrators would have remained in a cooler region if the grating had not sagged.

Air concentration estimates based on the Gaussian plume model were computed to provide an advance evaluation of potential off-site hazard. The release rate of DU was conservatively estimated to be 16 g/s, based on the preliminary bonfire test in which about 33% of the test penetrator was transferred either to ash or to an aerosol form. It was assumed that a maximum of 50% of DU in the fire would be aerosolized and this provided the basis for calculating maximum air concentrations. Other parameters entering the calculated estimates of air concentration were the source height (estimated to be 5 m), wind speed 3 m/s, and Pasquill's atmospheric stability category C. Atmospheric category C (slightly unstable) represents a conservatively poor diffusion condition.[3] Late August, when the test would be carried out, typically would have conditions providing a higher dispersion coefficient. Figure 2 presents concentration isopleths based on these parameters. The inner isopleth represents 10^{-4} g/m^3 and lies close to the nearest uncontrolled (also unpopulated) area, which was 1829 m away from the test site. The threshold limit value (TLV) for uranium, 2 x 10^{-4} g/m^3, would not be exceeded at that point.[4] This analysis provided ample conservatism since the TLV represents an allowable 8-h exposure and the calculated concentration of 2 x 10^{-4} g/m^3 would be short duration exposure. Worst case calculations using lower wind velocity and neutral stability indicated the advisability of (1) providing respiratory protection for onsite test personnel and (2) postponing the test if wind velocity was below 3 m/s and high stability persisted.

To avoid performing the test under worst case conditions, weather conditions were observed several days before the test by continuously recording wind velocity and direction at R-Site. Free-lift balloons were released immediately prior to the test to indicate wind direction and probable rise charactistics of the smoke plume.

Full-time, real-time color movie documentation of the bonfire cookoff test was obtained from an observation point 508 m from the bonfire. Two cameras were operated about 30 min at 24 frames/sec. Still photographs (8 black and white, 44 color) were taken of various aspects of the test, including telephoto from the observation point and closeups of fragments and bonfire residues. Twenty-six color photos for still documentation and the movie film have been sent to AFATL, Eglin AFB.

Instrumentation of the bonfire cookoff test consisted of five high-volume air samplers close to the bonfire and four thermocouples placed on the surfaces of the ammunition cans. Three high-volume air samplers were connected to 6.1-m-long steel pipes

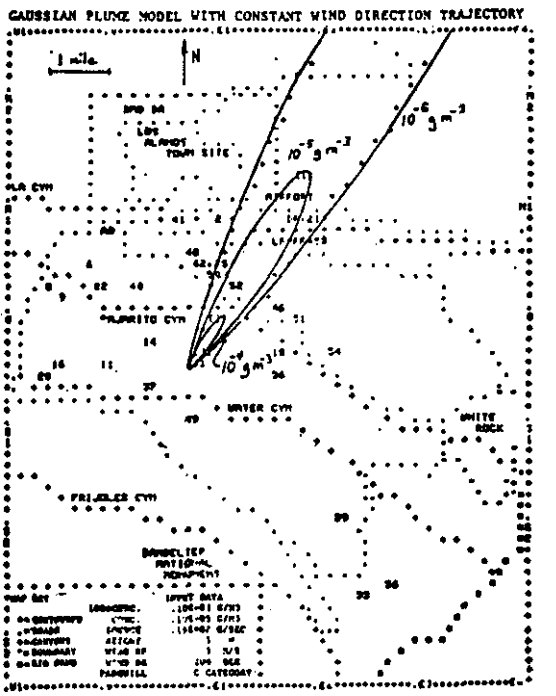

Fig.2.
Results of Gaussian plume calculations for nominal case.

connected as inverted L's on utility poles to act as probes. These probes projected over the fire to collect air samples without being disabled by heat or shrapnel. Large glass fiber filters (20 x 25 cm), which can operate at high temperature, collected the aerosol with very high efficiency. The three pole-mounted samplers were operated at a flow rate of 0.0165 m^3/s, with the probe intake about 7.6 m above ground. Two other high-volume samplers (capacity 0.033 m^3/s) were located 1.0 m above the ground about 21 m downwind of the bonfire. Figure 3 shows overall arrangement of the stack and sampler probes.

Table II lists the samplers and locations of the probe intakes during the test. The hinged feature of the pole-mounted probes permitted adjustment of the sampler intake to account for the wind direction at the start of the test. Azimuth is referenced clockwise from true north.

TABLE II

AIR SAMPLER DESCRIPTION AND LOCATION

Sampler	Description	Distance from Bonfire (ft)	Azimuth (deg)	Run Time (min)
1	5.1 cm i.d. probe	21	100	97
2	5.1 cm i.d. probe	22	20	97
3	3.8 cm i.d. probe	41	230	87[a]
4	open-face	70	225	97
5	open-face	70	230	97

[a]Starting time intentionally delayed 10 min.

IV. RESULTS AND DISCUSSION

A. Test Sequence and Temperature History

Wind velocity and direction were highly variable in advance of the test, ranging from 1 to 3.5 m/s and coming from the northeast quadrant. Wind velocity was considered acceptable, but its direction was not ideal because (a) the pole holding primary samplers (1 and 2) had been located in anticipation of the prevailing southwest wind, and (b) nearby office buildings and the observation point for the test were almost directly downwind of the bonfire. However, free-lift balloons released just before the scheduled test time remained generally south of these sites and exhibited consistently rapid rise. Since Samplers 3, 4, and 5 could be relocated for these existing conditions, and the weather forecast indicated similar conditions for the next two or three days, the decision was made to perform the test as scheduled on August 26, 1975.

The squibs were fired at 11:47 a.m.; samplers and recorder were started at 11:51 a.m.; and the first shell case disruption came at 11:57 a.m. Shell case disruptions ceased at 12:07 p.m. The bonfire was approached to 100 ft at 1:15 p.m. and extinguished by water spray at 1:45 p.m. Samplers were stopped at 1:28 p.m. after 97 min of operation. No brushfires were started in the area.

A photograph of the bonfire midway through the burn is presented in Fig. 4.

The temperature recorder (and samplers) was started 4 min after squib firing. Temperature history is summarized in Table III. All four thermocouples responded but only No. 1 and No. 3 reached the expected temperature. Table III indicates peak temperatures and the temperature 10 min after squib firing, to correspond (within ±1 min) with the first shell disruption. Thermocouple 1 was located

Fig. 3.
Overall arrangement of stack and samplers.

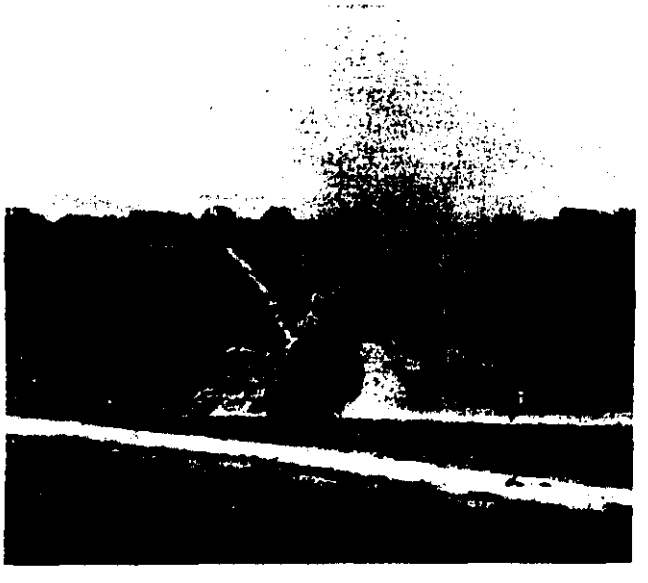

Fig. 4.
Telephoto of the bonfire midway through burn.

TABLE III
TEMPERATURE INDICATION

Thermocouple	Peak Temp °C	Temp °C @ 10 Min
1	875	795
2	525	350
3	905	905
4	705	400

between ammunition cases and the remaining thermocouples on outside surfaces of the cases. Indicated temperature began to gradually decrease soon after the first shell case disruption either because the thermocouples were disabled or were exposed to cooler gas after the kindling stack started settling.

B. Test Observations and Pattern Scoring

Observations of shell, projectile, shell base, and fragment locations within a 30-ft radius of the bonfire were made by Air Force personnel. The following statements summarize their findings:

1. About 90% of all projectiles were recovered within the 30-ft radius.
2. Furthest projectile was located at 70 ft.
3. About 20% of all penetrators were affected by visually detectable mass loss.
4. Twenty unexpended shells were located, all within 30 ft.
5. Two primers remained live in disrupted shells.
6. Many shell case fragments and shell bases located within 30-ft radius were not scored.

A subsequent inventory of the penetrators produced the breakdown listed in Table IV. All 180 penetrators were located. Fifty-three of the 180 penetrators (30%) lost DU in visually detectable amounts; several penetrators were almost totally consumed while others were almost intact. A mass balance for DU was not practical because large amounts of fused aluminum adhered to some penetrators. Fused masses containing multiple penetrators were formed in the bottom of ammunition cans as melted aluminum parts flowed around the penetrators. Figure 5 shows several badly burned penetrators and fused masses.

TABLE IV
PENETRATOR INVENTORY

Description	Number
Unexpended shells	20
Unburned penetrators	107
Burned individual penetrators	26
Fused Mass A	9
Fused Mass B	4
Fused Mass C	6
Fused Mass D	8
Total	180

Shell bases and fragments in the graded area (full circle from 30 to 100 ft) were located by azimuth (±1°) and distance from center (±1 ft) with tape and transit. These locations are plotted in Fig. 6. In the semicircle from 100 to 400 ft, locations were logged with transit and level rod (stadia method) to the same accuracy (see Fig. 7). Total numbers of fragments and shell bases located in these areas are listed in Table V. The shell base projected farthest from the bonfire (465 ft) is shown in Fig. 8.

A small fragment (about 3 x 5 cm) was located the day following the test ~700 ft from the bonfire. This is 350 ft beyond any other fragment location in this test and 240 ft beyond any fragment location in three earlier tests performed at Eglin AFB on similar ammunition containing the same cartridge case and equivalent propellant load.[5] The low mass of the fragment and its extreme distance from the bonfire suggest that this is an artifact due to some mechanism of transport other than ballistic projection. Wildlife in the area, ravens in particular, are frequently attracted to shiny metal objects such as this fragment, and are known to move objects even larger than this fragment. We consider this the probable explanation and have omitted this fragment from pattern scoring of the test. Complete scoring data sheets have been forwarded to AFATL, Eglin AFB.

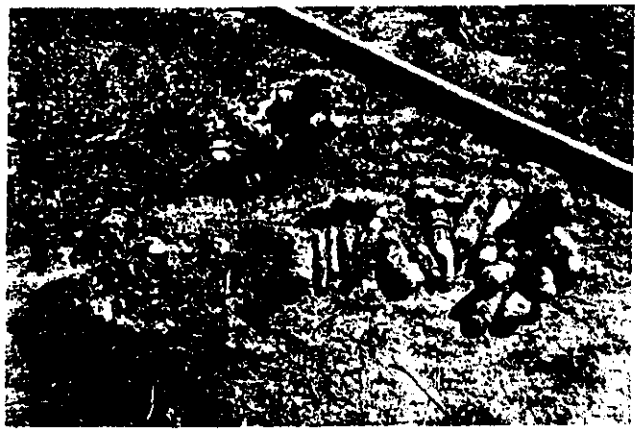

Fig. 5.
Penetrators and fused masses recovered from the bonfire.

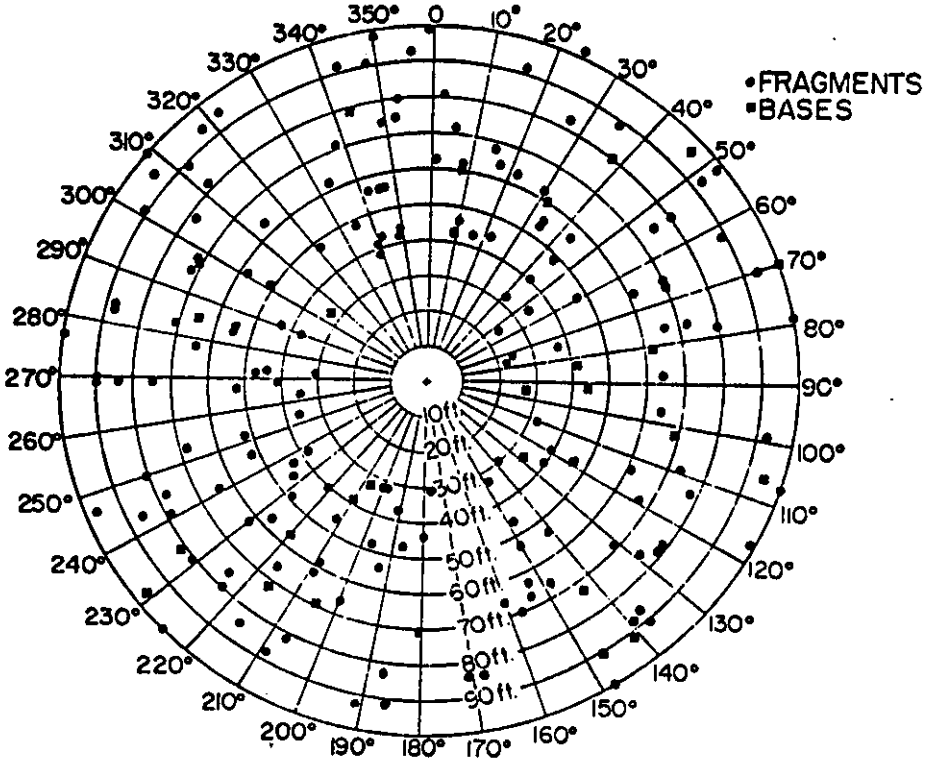

Fig. 6.
Pattern scoring of the 100-ft-radius circle.

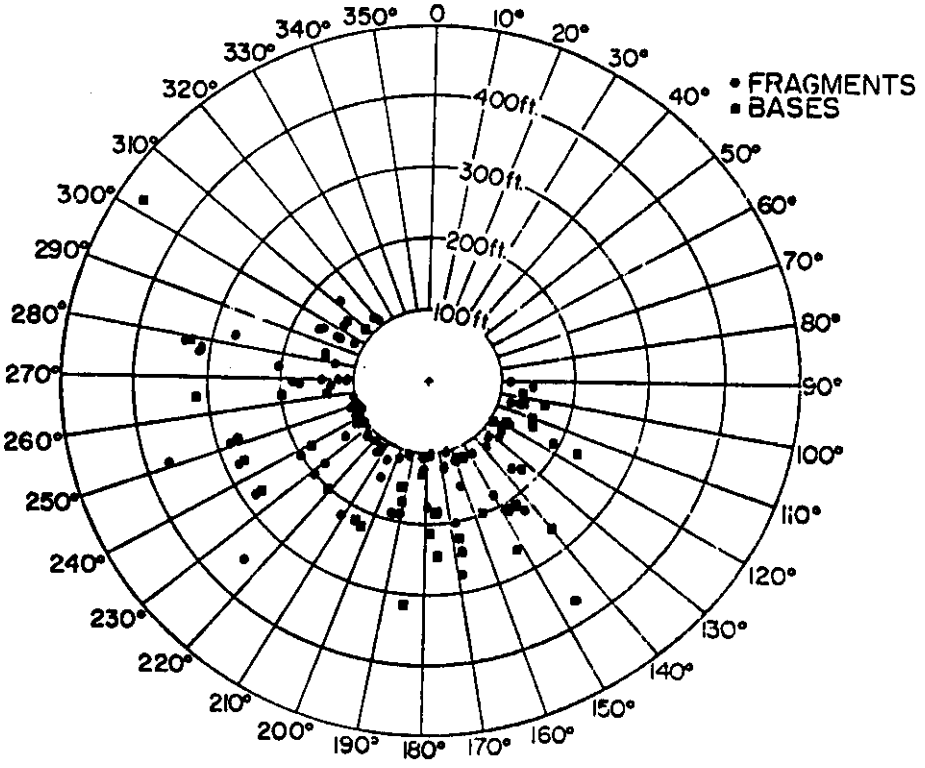

Fig. 7.
Pattern scoring of the 400-ft-radius semicircle.

TABLE V

FRAGMENT SCORING TOTALS

Area	Shell Bases	Fragments
30–100 ft (360°)	33	163
100–400 ft (180°)	41	71

C. Air Sampling Results

The limited objective of air sampling to detect DU aerosol was realized when all five air samplers showed positive indication of uranium. The results of mass determinations of uranium collected either on the glass fiber filters (Samples 1-5) or washed with water from the probes of Samplers 1, 2, and 3 (Samples W1-W3) are presented in Table VI. Total aerosol masses (ash and DU) collected on the filters are included for comparison. It should be emphasized again that the sampling network was designed solely to confirm the presence of DU aerosol and, being deficient both in number and type of samplers, could not provide data for a quantitative estimate of total DU released to the atmosphere.

Sample analysis was accomplished by acid leaching all deposited material from the glass fiber filters (including material filtered from wash water) and analyzing for uranium. Samples electroplated onto counting planchets were analyzed radiometrically above a detection limit of about 7 μg. If the sample activity was below this detection limit, a fluorophotometric method with much greater sensitivity (about 0.1 μg) was used.[6] This method, based on intense yellow-green fluorescence at 555 nm of the uranium-sodium fluoride system, was subject to interference by iron from the probes, necessitating extraction of uranium by a liquid ion

Fig. 8.
Shell base located at 465 ft.

TABLE VI

URANIUM COLLECTED ON HIGH-VOL SAMPLES
GAU-8 BONFIRE COOKOFF TEST

Sample No.	Uranium Mass (mg)	Total Mass (mg)
W1[a]	0.102[b]	NM[c]
W2[a]	0.018[b]	NM[c]
W3[a]	0.015[d]	NM[c]
1	0.0014[d]	89.6
2	0.0021[d]	78.9
3	0.0012[d]	17.7
4	0.0046[d]	7.7
5	0.0033[d]	19.4

[a] Washed from probes of samplers 1, 2, and 3.

[b] Determined radiometrically.

[c] Not measured.

[d] Determined fluorophotometrically.

exchange technique. This technique recovered 79% of uranium in a standardized (spiked) sample. The results reported in Table VI have been corrected by this recovery factor. Since Samples W1 and W2 did not show adequate extraction for fluorophotometric analysis, their radiometric results are reported. Sample W3 showed good correlation between radiometric (19 μg) and fluorophotometric (15.3 μg) methods.

The filters had collected relatively light deposits; that is, none was near plugging. Highest amounts of DU were found in the probes. Collection of DU by impaction at the elbow and turbulent impaction along the probe was expected owing to Reynolds numbers far above the 2000 to 2800 range for best transmission of particles. A nominal flow rate of 0.0165 m^3/s in a 5.1-cm pipe produces a Reynolds number near 10 000 (gas temperature was assumed to be 200°C). Although reduction of sampling flow rate and/or an increase of the probe diameter could have achieved ideal flow conditions and attendant low deposition, retention of high sample volume and recovery of deposited material by probe washing was selected as the more suitable approach.

All samples showed positive indication of airborne DU. The lowest measured air concentration, based on Sampler 5 results, was estimated to be 20×10^{-6} mg/m^3, compared to maximum concentrations of natural atmospheric uranium in the range 0.07 to 0.25×10^{-6} mg/m^3 measured during 1974 at five LASL technical area stations and ten stations around the perimeter of the LASL complex.[7]

Analysis of the data beyond the simple conclusion of a DU aerosol being present is not supportable, considering the limited number of data, different sampler heights and distances, different inlet losses, and wind speed and direction variability.

V. SUMMARY

Results of a bonfire cookoff test of GAU-8 ammunition with DU penetrators provided fragment mapping and confirmed the release of a DU aerosol. Determination of size characteristics and mass concentration of the DU aerosol was not a goal of the test. The first shell case disruption occurred about 10 min into the test when indicated temperature had reached 900°C. Disruptions ceased about 10 min later. All but one fragment (a shell base) remained within 400 ft of the bonfire.

DU penetrators underwent pronounced mass loss due to high temperature exposure in the bonfire. About 30% of the penetrators lost visually detectable amounts of DU. The remainder of the penetrators was transferred by explosive reaction to regions of lower temperature. Almost total dispersion of several penetrators to aerosol and ash illustrated the probable fate of any penetrator remaining in a high temperature region.

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